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Abstract

The quality of the sunlight spectrum can be modulated by incorporating optically active formulations into plastic greenhouse covers with the objective to improve plant precocity, yield and fruits' quality. The patented "Light Cascade®" (LC®) technology formulations, which are dispersed in plastic greenhouse films, can induce an increase in the Blue (400-500nm) and in the Red (600-700nm) wavelengths. This study aims to evaluate the effect of the LC® technology on the productivity of two low tunnel cultivated crops, i.e. the Charentais cantaloupe melon and early culture of potato. For each crop, trial campaigns have been performed since 2015 at different experimental and growers' farms in France and Spain. Several LC® formulations have been evaluated and next to their optical properties, the lifetime of the LC® systems was significantly improved. First and/or final cumulated yield (T/ha) of each crop has been quantified and melon fruits' quality has been assessed based on the sugar content quantification and weight. Melon trial results showed a weather conditions and region-specific response underneath the LC® films. The main data indicated (i) an increase of up to 2,2 times yield at the first melon harvest, (ii) an increase of the mean fruit weight (+34,4g) for all harvests and (iii) a stable or an increased sugar content relative to the conventional film. More interestingly, the effect of the LC® greenhouse films on melon production was more pronounced in unfavourable climatic conditions and seems to be temperature dependent. Concerning the early potato crop results, two very interesting results have been observed as (i) an earlier harvest time (8 days) and (ii) an increase of small sized tubers' yield (up to 15%). Further research is ongoing to evaluate the effect of the LC® additives on other greenhouse cultivated crops, such as berries, tomato, pepper, cucumber and cut flowers. Next to this, a better understanding of the temperature effects and light intensity on the performance of the LC® greenhouse films is investigated.

Key words: Light spectrum, optical active dyes, Photosynthetically Active Radiation (PAR), vegetable, photoconversion greenhouse covers

INTRODUCTION

Crop production optimisation can be achieved by the manipulation of one of the most important factors that controls growth and development of plants: the light (Smith, 1982). Light quality and intensity both influence two different aspects of plant's life: photosynthesis and photomorphogenesis. Photomorphogenesis is considered to exert an effect on several plant development aspects such as height, leaf size and flowering. Different key photoreceptors controlling photomorphogenesis have been identified in plants: UVR8 (sensitive to UVB radiations; 290-320 nm), Cryptochrome, Phototropins, Zeitlupe, Flavin binding Kelch and Lov Kelch proteins (sensitive to UVA and Blue wavelengths; 320-500nm) and phytochromes (sensitive to Red light (~650-670nm), Far Red light (~705-740nm) and to a lesser extent Blue light (400-500nm)) (for review, Huché-Thélier et al. (2016) and Demotes-Mainard et al. (2016)).

By contrast, photosynthesis is generally associated to plant growth and involves the two main photosynthetic reactions centres, the photosystems I and II that contain different chlorophyll and carotenoid pigments, involved in light capture and transfer. These pigments have their own light absorption specificities: chlorophyll *a* and *b* mainly absorb in Blue (peaks 430 nm and 453nm respectively) and Red (peaks at 663nm and 642 nm respectively) and less in Green

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(between 520nm-560nm). β carotene and lutein pigments absorb essentially Blue radiations (maximum peaks at 454nm and 448nm respectively).

It is generally considered that the spectral activity range for plant photosynthesis is from 400 to 700nm which is defined as the PAR (Photosynthetically Active Radiation) (McCree, 1972) and corresponds to the integration of photosynthetic photon flux values (or PPFD expressed in $\mu mol.m^{-2}.\ s^{-1}$). An increase of the PPFD favours photosynthetic rate which is conditioned by the light compensation and light saturation points. Light compensation point is the value at which the photosynthetic activity equals the plant respiration activity and the light saturation point corresponds to the light intensity at which the photosynthetic rate reaches the maximum. Consequently, it can be admitted that an increase of the photosynthetic rate favours plant growth and most of the time an increase of plant yields.

Different light modulating systems, that might enhance plant photosynthesis, are available in horticulture such as incandescent and fluorescent bulbs, high pressure sodium lamps (HPS) and LED but also photoselective and photoconversion greenhouse covers can be employed, as on peach and cherry culture (Schettini et al., 2011). Electrical supplemental lighting are interesting tools to improve crop production. Indeed, the extension of the photoperiod or enhanced light intensity inside the greenhouse enabled to increase the crop yields, especially in northern latitudes during late autumn, winter and early spring seasons when the sunlight is insufficient. However, the increased yields need to compensate the energy cost induced by the electrical lighting system supplementation (Eichhorn Bilodeau et al., 2019).

The use of light filters or photoconversion films that modulate the incident sunlight might be a cost-effective alternative to electrical lightings. Besides, these films are suitable for open field productions. Many studies focused on the effect of the Red/Far Red modulation on growth and development of different crops (such as tomato, pepper, chrysanthemum and others) or by photoselective shade nets that protect the crop from excessive light, wind, hail and pests. Interestingly, the 'ColorNets', developed by Polysack Plastic Industries, might alter light quality and intensity by absorbing UV, blue, green, yellow, red, far red or infrared wavelengths by the incorporation of pigments inside (Rajapakse and Shahak, 2007). However, relatively few studies evaluated the effect of gains in Blue and/or in Red wavelengths induced by photoconversion plastic covers (Novoplansky et al., 1990; Espí et al. 2006; Hidaka et al., 2008; Nishimura et al., 2012). To our knowledge, no studies evaluated the effect of this kind of films on melon and potato crops in open field conditions.

In this context, the French company CASCADE developed the patented 'LIGHT CASCADE' technology (or LC® technology), constituted of optical active dyes that convert UV and Green wavelengths into Blue and Red respectively. Once the LC® technology is incorporated into the plastic greenhouse covers, the light spectrum intercepted by the crop is enriched into these two wavelengths.

This study aims to evaluate the effect of low tunnel plastic covers with the LC® technology on the Charentais cantaloupe melons crop yield and fruits quality in France and Spain, and on early potato crop in France.

MATERIAL AND METHODS

The principle of the 'LIGHT CASCADE®' technology

The patented 'LIGHT CASCADE®' (LC®) technology has been created by CASCADE in 2013. Each year, different formulations have been tested and optimized with regards to dye composition and concentration level, according to the obtained agronomic results. CASCADE develops its own formulations and dispersions in polymer matrices, resulting in masterbatches that are further dispersed in foils. This step is realised by film conversion companies such as Trioplast (49, France) and AGRIPOLYANE (42, France). Here, multi-layered films of PE (polyethylene) and EVA (ethylene vinyl acetate copolymer) have been tested with the LC® technology (Figures 1,2).

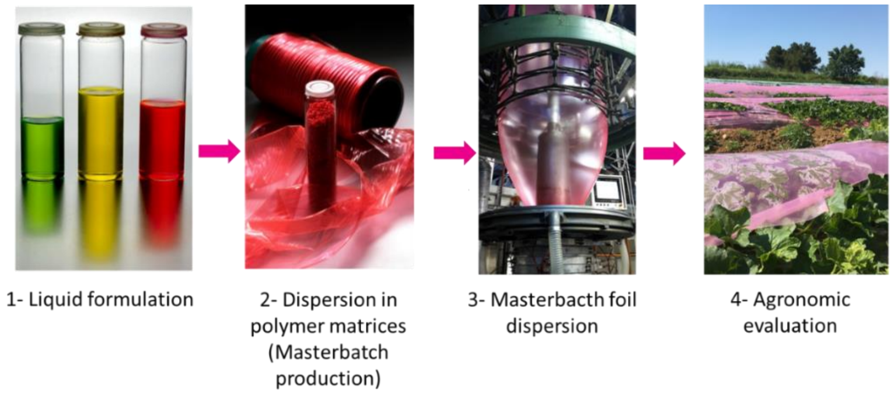

Figure 1. Steps required for films manufacturing with the LC® technology.
CASCADE elaborates the aimed formulation (1) which is then integrated into plastic polymers to constitute a master batch (2). The master batch is then dispersed into the films during the extrusion process (3). Finally, the films with the LC® technology are evaluated in real open field conditions (4).

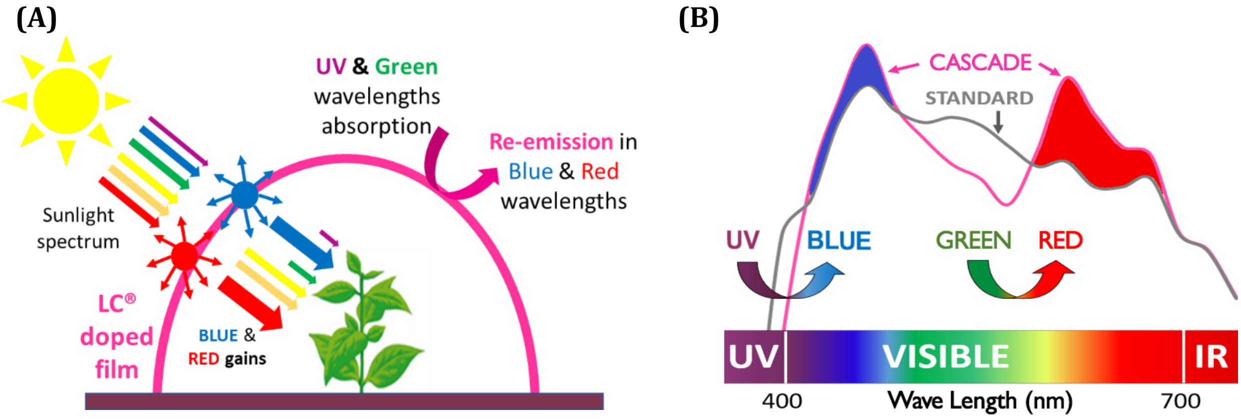

Figure 2. Illustration of the effect of the LC® technology on the solar spectrum.
The LC® technology converts a part of the UV into Blue and Green wavelengths into Red.

Owing to confidentiality reasons, the exact composition of the LC® technology and the corresponding spectral modifications of each LC® formulation described in this study cannot be detailed. The LC® formulations presented here differentiates each other by the gains in Blue and Red and their lifetime. Plastic covers transmission is not modified by the technology (Figure 2).

Test of the different LC® formulations integrated in low tunnels films

1. Potato trials.

The potato trials have been setted up in Noirmoutier en L'Ile (85, France) from 2016 to 2018 to evaluate the effect of the LC® technology on tubers production of the early (or 'primeur') potato crop *Solanum tuberosum* cv. 'Sirtema'.

Four different LC® formulations, incorporated into 80 µm films, have been tested each year: 'PT16_1' and 'PT16_2' in 2016, 'PT17' in 2017 and 'PT18' in 2018. The PT16_2 films were more concentrated in LC® formulation than the PT16_1 films. The transmission is identical with the added additives but there is more light in the PAR by the photoconversion mechanism. The corresponding conventional film (without the LC® technology) has been included during each trial campaigns. Each year, the films' installation occurred from the mid-January to the mid-April.

The experimental design consisted on at least 2 low tunnels (width: 2,1m, length: 10m to 150m according to the field size) of each type of film in one different field per year.

Tubers' weight (in g/plant) and size (below 35mm, between 35mm to 55mm and above 55 mm) have been determined on 7 plants per tunnel during the 2016 and 2018 trials. The number of tubers per plant has not been determined.

Only visual observations have been realised during the 2017 trial.

No climatic data inside the low tunnels have been recorded during these 3 trials. For each trials, temperature and the cumulative daylight integral (DLI) values obtained from the Power Data Access Viewer website (**https://power.larc.nasa.gov/data-access-viewer/)** are presented in the Figure 3.

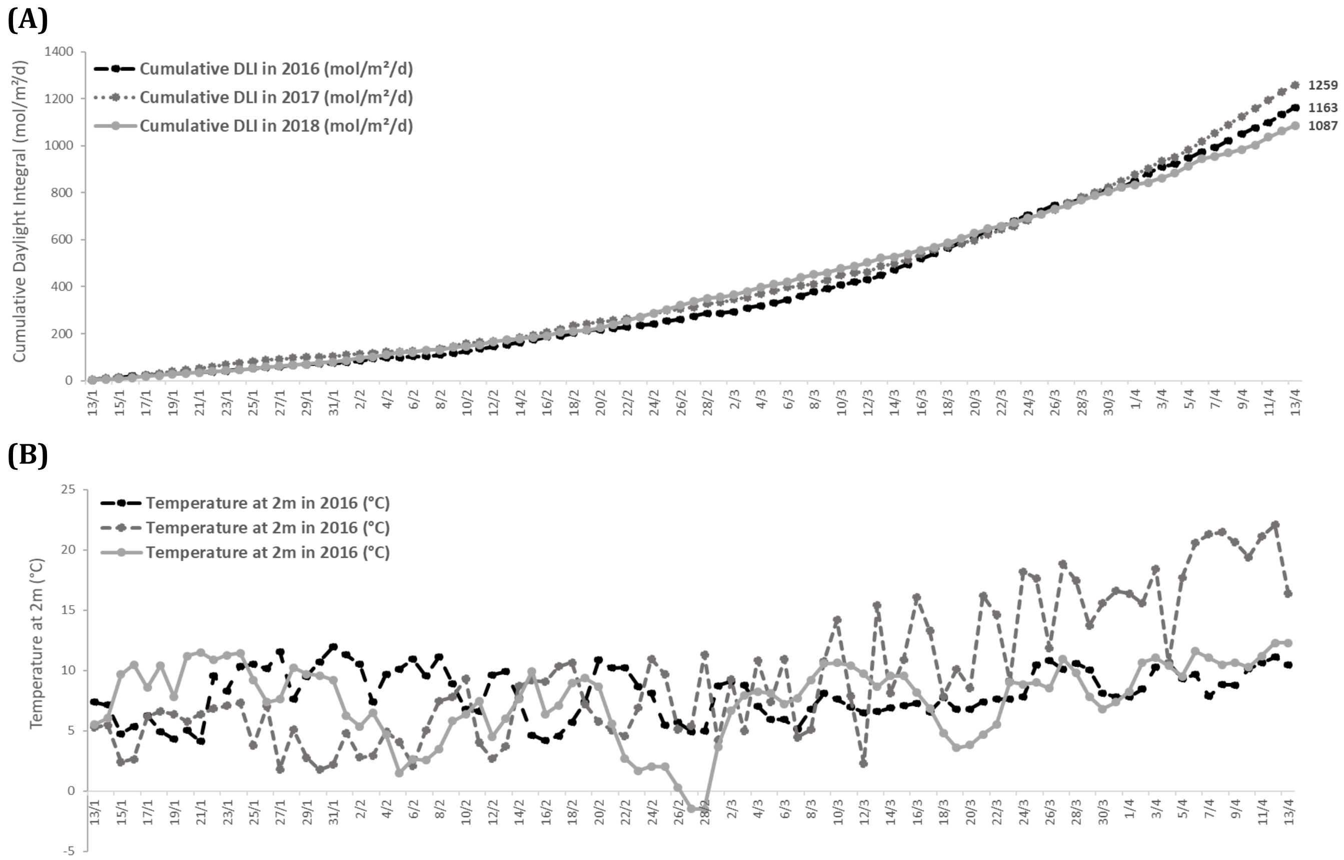

Figure 3. Cumulative Daylight Integral (mol/m^2/d) (A) and mean of the temperature at 2 meters (B) obtained during 13th of January to the 13th of April period in 2016, 2017 and 2018. Source : **https://power.larc.nasa.gov/data-access-viewer/**

2. Melon trials.

Nine Charentais cantaloupe melons (*Cucumis melo* L., var. *cantalupensis* Naud.) trials have been mainly realised in France (Western and Southern France) and in Spain (Malaga and Murcia) by three experimental centers (SudExpé, "Station de Recherche Appliquée Fruits et Légumes, Marsillarges" (34, France), GDM, "Groupement Développement Maraîcher', (85, France) and IMIDA, "Instituto Murciano de Investigación y Desarrollo Agrario y Alimentario", Murcia, Spain) or in farmers' field conditions ('Force Sud' in Southern France and 'Rouge Gorge' in Malaga, Spain) (cf Table I). Six melon cultivars have been tested: 'Silvio', 'Escobar', 'Gandalf', 'Alonso', 'Belharra' and 'Arpon'. For each trials, the cumulative degree days and the cumulative daylight integral are detailed in the Table 1 (determined from the Power Data Access Viewer website t **https://power.larc.nasa.gov/data-access-viewer/)**.

Seven LC® formulations have been tested: M15 in 2015, M16 and MC16_1 and MC16_2 in 2016, M17 in 2017 and M18_1 and M18_2 in 2018. Films installation took place in the beginning-mid January/February in Spain, in March in Southern France and in April in Western France.

The MC16_2 and M18_2 films were more concentrated in LC® technology in comparison to the MC16_1 and M18_1 films respectively. The films characteristics were 50µm of thickness and a width of 2,1m.

At least 4 independent replicates have been tested per type of film in which one replicate corresponds to one low tunnel of 10 meters to 2400 meters long according to the trial. The films have been tested from 68 days to 93 days on the crop, according to the variety considered.

Different parameters have been evaluated: the number of growing fruits counted along 10 linear meters per replicate, the yield at the first harvest (in T/ha), the final cumulative yield (in

T/ha), the mean of fruit weight (in g) and the sugar content (in °Brix) of at least 6 fruits picked on 2 independent harvests campaigns.

RESULTS AND DISCUSSION

Potato trials results

During these 3 trial campaigns (2016 to 2018), the cumulative DLI values showed relatively limited sunlight intensity in January and February (Figure 3A). At the end of the 2018 trial, the cumulative DLI was slightly less (1087 mol/m^2/d) in comparison to 2016 and 2017 (1163 and 1259 mol/m^2/d respectively) (Figure 3A).

For each years, an advanced growth and development of the aerial vegetative part under the different LC® films in comparison to the conventional film. Consequently, this advanced growth and development resulted in 8 days earlier harvest under the LC® films. No phenotypic measurements have been realised during these 3 trials, only visual observations.

Interestingly, in 2016, the 2 formulations PT16_1 and PT16_2, increased the yield for the <35mm category (+15% and +12% respectively); however, the PT16_1 films reduced the tubers' yield for the other 2 categories (-11% for 35-55mm and -72% >55mm) in comparison to the PT16_2 films (+8% for 35-55mm and +9% for >55mm). According to these results, the 2017 and 2018 formulations have been developed based on the PT16_2 formulation (Figure 4 A, C).

In 2017, the tubers advanced harvest has been confirmed but the yield has not be quantified.

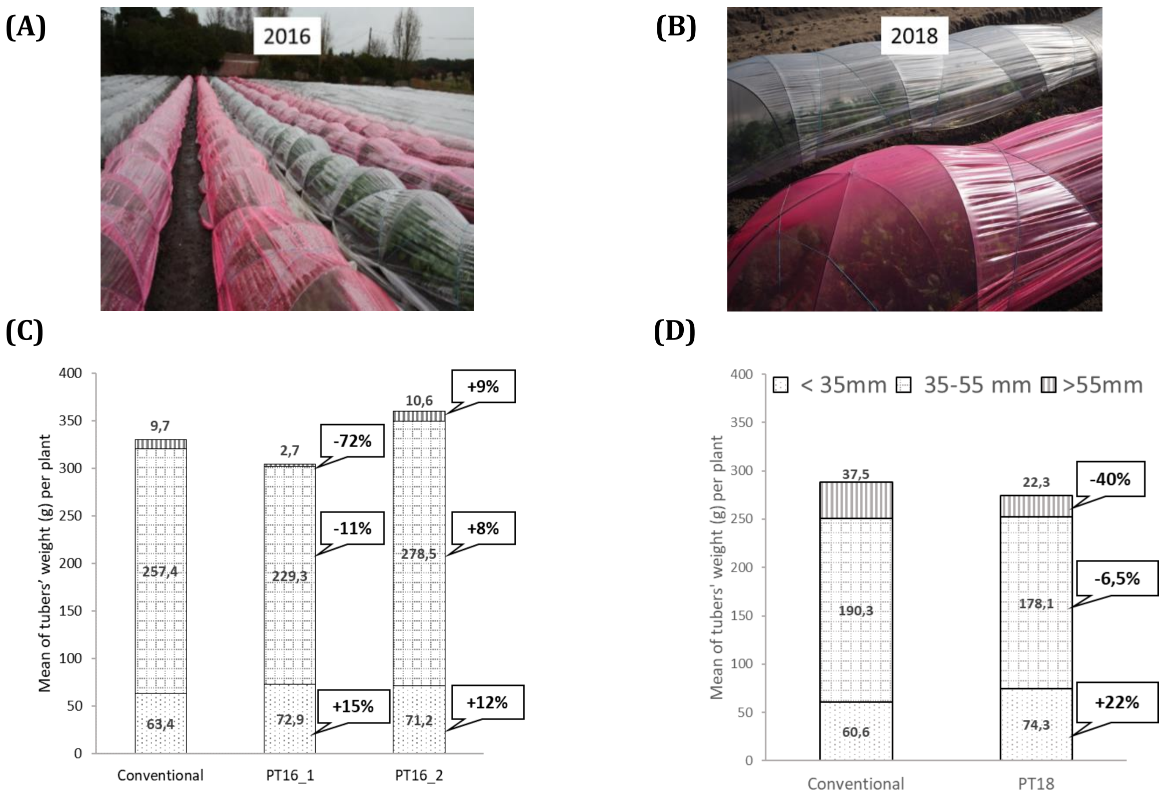

Figure 4. Illustration of the potato trials in 2016 (A) and 2018 (B) and the corresponding mean of tubers weight (in g/plant) obtained from 7 plants in 2016 (C) for the conventional, PT16_1 and PT16_2 films and 2018 (D) for the conventional and PT18 films.

In 2018, the results indicated an increase (+22%) of the <35mm tubers weight but a reduction for the other 2 categories (-6,5% for 35-55mm and -40% for >55mm) in comparison to the conventional film (Figure 4 B, D).

The 2018 reduced yield under the PT18 films might be explained by the negative temperatures which occurred at the end of February 2018 (Figure 3B): the frost damaged the potato plants and appeared more severe under the PT18 film in comparison to the conventional film (Figure 5A). Interestingly, before this freezing period, the potato plants were more developed and in advance under the PT18 films in comparison to the conventional film.

The LC® technology did not modify the temperatures below the tunnels (data not shown). Consequently, it might be hypothesized that the highest sensitivity of potato plants to the frost under the LC® tunnels might be due to the advanced growth stage in comparison to the conventional cover.

In this situation, the damaged plants under the LC® films might recovered less quickly in comparison to the conventional films and consequently produced reduced tubers' yields.

Globally, it can be concluded that the LC® films tend to favour (i) early tubers harvest, an (ii) increase of the <35mm yield and (iii) a reduction LC the >55mm yield.

The effect of LC® films on tubers size reduction is economically interesting for the producers because of the early produced small sized tubers (<35mm) have a higher economic value in comparison to the >55mm in France in Noirmoutier (Figure 5B).

(A)

(B)

Size (mm)	Mean of price (€/kg) (2016, 2017 & 2018) Beginning of April	End of April	Average
<35	5,0	3,7	4,3
< 55	3,8	2,6	3,2
>55	1,4	0,7	1,0

Source : Coopérative de Noirmoutier (29th June 2018)

Figure 5. Illustration of the frost damages on potato plants during the 2018 trial (A) and the mean of 2016 to 2018 tubers price for each category (<35mm, <55mm and >55mm) (B).

Melon trials results

Globally, on 9 trials, 7 had at least one LC® formulation that induced positive effects on melon marketable yield and 2 slightly decreased it (Table 1). Indeed, the yield obtained at the first harvest under the seven LC® films was in average 2,2 times higher than the conventional film. which corresponds to a gain of approximately 30% (Table 1). The effect of the LC® films on final cumulative yield ranged from -3% to +25% with an average of +3.3% in comparison to the conventional film (Table 1).

Concerning the quality, the sugar fruits content was almost unchanged or, in some cases, slightly improved (GDM trial, M15 films, Table 1). For the fruits weights, an average gain of +34,4g has been observed under the LC® films for all harvests (Table 1).

An important yield gain of about +25% has been observed in 2016 in Western France (GDM trial) and in Spain (Rouge Gorge trial, 2018, M18_2 films) and up to +8% in the South of France (Sudexpé trial, 2016, MC16_2) (Table 1). Interestingly, a normal marketable yield approximates 20T/ha. For these trials, the yield was extremely low (11-12T/ha). These results might be explained by the fact that the LC® films enhanced plant growth and development under unfavourable climatic conditions by increasing the light quantity in Blue and Red regions of the solar spectrum.

Indeed, according to the climatic data, in Western France, low temperatures in April and May 2016 and the heavy rainfalls particularly at the end of May (up to 50mm) have been registered. During this trial, fruits initiation and development occurred at this unfavourable period. For melon production, growers know that fruits development is a critical stage and is light and temperature sensitive. In May 2016, the GDM noticed an increased number of the swelling fruits under the LC® cover in (Table 1). In the same way, in Malaga, heavy rainfalls and weak temperatures occurred in March 2018; which explain the relative low cumulative degree days at the first harvest (117°C) (Table 1). Consequently, under these conditions, it can be hypothesised that the LC® covers favoured melon plant growth/fructification.

The positive effect of the IMIDA 2017 trial in Spain has been observed only on melon fruit weights (+202g) under the LC® films. These results can be explained by the fact that the PTM17 film has been applied relatively late (i.e. in February 2017) and the climatic conditions were favourable to the melon crop in Murcia with a high cumulative degree days at the first harvest and last harvest (723°C and 1228°C respectively) (Table 1). The M17 formulation did not seem not favour the first harvest yield (2.5 T/ha under the M17 film and 6.2T/ha under the conventional). At this moment, the exact interaction between the LC® technology effect and the temperature on the melon crop is still unclear. In this situation, it might be supposed that high temperatures and gains in Red might be unfavourable to the early melon harvest yield.

In the South of France, the Force Sud 2018 trial results showed that the final cumulative yield with the less concentrated LC® formulation M18_1 was better in comparison to the one obtained with the M18_2 formulation (+17,2% for M18_1 versus -3% for M18_2) (Table 1). Interestingly, the number of developing fruits was higher under both LC® films (+26% for M18_1 and +21,7% for M18_2) in comparison to the conventional film. In other words, it might be supposed the growing fruits under the M18_2 did not swelled and/or ripened correctly: they may be aborted or were insufficiently developed when the harvests were realised.

CONCLUSIONS AND DISCUSSION

This study highlights the benefits that can be provided by the photoconversion films on two crops cultivated in open field conditions. An increase of the yield as well as the production quality has been observed for the potato crop (i.e more small sized-tubers and earlier tubers harvest) which is a particular interest from the growers (higher economic value of small sized tubers in the beginning of April) and for the customers (the earliest potato product in France of the year).

Concerning the Charentais cantaloupe melon crop, the different LC® formulations provided positive effects on the first harvest yields (average of a gain of 30%) and under unfavourable climatic conditions, the final cumulative yield might be increased up to 25%. Interestingly, yields gains did not seem to negatively affect the fruits quality (weight and sugar content). However, differences in the effects of two different concentrated LC® formulations on crop yields under the same trial condition remain to be explained. The temperature seem to modulate the LC® effects; further investigations are required to better understanding it.

The CASCADE company is currently testing the effect of its technology on other crops such as the winter cultivated Spanish cucumber, zucchini, pepper, and tomato crops, as well as berries (strawberry, raspberry and blueberry) essentially in Spain and France (Lemarié et al., 2018). The first 2019 results confirm the positive effects of the LC® films on these crops particularly during winter reduced light intensity conditions.

A new funding (ECLA, convention n° 1882C0029) from ADEME ('Agence De l'Environnement et de la Maîtrise de l'Energie', Angers, France) has been obtained in September 2018 in order to (i) better understanding the effects of the current LC® formulations on the different crops, (ii) evaluate potential benefits on plant nitrogen use efficiency and plant resistance and (iii) improve the LC® lifetime in order to produce multi-season films (berries high tunnel for ex.).

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Table 1. Effects of the different LC® formulations on the Charentais cantaloupe melon crop.

Year	Variety of melon 'charentais'	Location	Experimental farm or Producer's farm	Cumlative degrees at the first harvest	Cumlative degrees at the last harvest	Cumlative DLI at the first harvest	Cumlative DLI at the last harvest	Number of swelling fruits along 10 linear meters	% of difference between the LC® film in comparison to the conventional film	LC® formulation tested	Yield at the first harvest (T/ha)	% of difference in first harvest	Final cumulative yield (T/ha)	% of difference in final cumulative yield	Mean of sugar content of fruits (°Brix)	Difference between the conventional and the CL® films (°Brix)	Mean fruit weight (g)	Difference between the conventional film and the CL® film (g)
2015	SILVIO	Petosse (85) (Western France)	GDM	292	489	3244	4210	79	8%	Conventional	0,8	**187%**	22,4	**11%**	13	**1,1**	NA[1]	NA[1]
								87		M15	2,3		24,9		14,1			
2016	ESCOBAR	Petosse (85) (Western France)	GDM	**264**	496	**3292**	4516	31	13,40%	Conventional	3,2	**22%**	11,2	**25%**	15,3	-1,3	651	**5**
								44,4		M16	3,9		14		14		656	
	GANDALF	Marsillargues (34) (Southern France)	SUDEXPE	**42**	332	**2741**	4332	NA[1]	NA[1]	Conventional	3,8		11,8		15		668	
										MC16_1	4,3	**13%**	11,6	-1,7%	14,8	-0,2	662	-6
										MC16_2	2,3	-40%	12,8	**8,5%**	14,7	-0,3	704	**36**
2017	ALONSO	Marsillargues (34) (Southern France)	SUDEXPE	181	373	2760	3669	NA[1]	NA[1]	Conventional	0,6	**716%**	22,5	-6,6%	13,3	0,2	981	**47**
										M17	4,9		21		13,5		1028	
	ALONSO	Vouillé-les-Marais (85) (Western France)	GDM	213	347	3465	4085	53,1	3,30%	Conventional	8,5	**28%**	24,9	-3,4%	NA[1]	NA[1]	NA[1]	NA[1]
								56,4		M17	10,9		24					
	ALONSO	Murcia (Spain)	IMIDA	**723**	1228	**2234**	3581	NA[1]	NA[1]	Conventional	6,2	-59%	41,5	**2%**	13	-0,5	713	**202**
										M17	2,5		42,2		12,5		915	
2018	ALONSO	Vouillé-les-Marais (85) (Western France)	GDM	306	416	3066	3582	66	3,70%	Conventional	0,6	**100%**	14,6	**16%**	14,3	0,3	NA[1]	NA[1]
								69,7		M18_2	1,2		17		14,6			
	BELHARRA	Saint Thibéry (34) (Southern France)	Force Sud	225	367	2655	3447	46		Conventional	12,8		34,9		NA[1]	NA[1]	1 278	
								58	26,10%	M18_1	13,3	**4%**	40,9	**17,2%**			1 287	9
								56	21,70%	M18_2	12,4	-3%	33,8	-3,2%			1 305	**27**
	ARPON	Malaga (Spain)	Rouge Gorge	**117**	220	**2914**	3696	NA[1]	NA[1]	Conventional	4		12,4		14,3		800	
										M18_1	5	**25%**	12,6	1,8%	14	-0,4	810	10
										M18_2	8,2	**105%**	15,5	**25,6%**	14,5	0,2	780	-20
Average of the 9 trials with the different LC® formulations												**31%**		3,3%		**-0,1**		**34,4**

[1] Not available

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